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A NEW BROADBAND MICROWAVE FREQUENCY DEVICE FOR POWERING ECR ION SOURCES

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Abstract

Broadband *rf* injection offers a low-cost and effective method for increasing the physical sizes of ECR zones within ECR ion sources. Broadband radiation can also be used to ameliorate diamagnetic frequency detune effects that are believed to be problematical in single-frequency plateau ECR sources. An additive white Gaussian noise generator (AWGNG) system for injecting broadband *rf* power into these sources has been developed in conjunction with a commercial firm. The noise generator, in combination with an external local oscillator and a traveling wave tube amplifier (TWTA), can be used to generate broadband microwave power for ECR ion sources without requirements of modifying the injection system of these sources. The AWGNG and its initial use for powering the all permanent magnet, ORNL plateau ECR ion source will be described in this document.

INTRODUCTION

Energy can be transferred by microwave radiation to free electrons in an evacuated volume, submerged in an external steady-state magnetic field, at positions within the magnetic field distribution that meet the resonance condition, $\omega_c = Be/m_e = \omega_{rf}$ where ω_c is the electron-cyclotron resonance (ECR) frequency; ω_{rf} is the frequency of the microwave; B is the magnetic field intensity; e is the electron charge; and m_e is the mass of the electron. The regions where this condition occurs are referred to as ECR zones. Electrons that coincidently arrive in these zones in proper phase with the electric field vector of the electromagnetic wave can be accelerated to high energies. The ECR ion source (ECRIS) utilizes this electron heating mechanism as a means of creating high-charge-state ion beams through sequential electron removal. However, because of the continuously varying magnetic field distributions utilized for plasma confinement in conventional-*B* geometry, single-frequency ECR ion sources, the ECR zones are thin fluted shells that surround and intersect the axis of symmetry of the source at the injection and extraction ends of the source. The ECR zones in these sources are small in relation to the physical size of the plasma volume, and therefore, the microwave absorption efficiency is determined by the size of the embedded ECR zones. As a consequence of the small physical sizes of the ECR zones, the high-charge-state capabilities of these sources suffer because of the low probability for electron acceleration (stochastic). Several methods have been proposed to overcome limitations imposed by the small ECR zones [1,2]. ECR ion sources with enlarged ECR zones or increased numbers of ECR zones clearly outperform their conventional-*B* single frequency counterparts in terms of high-charge-state capabilities as evidenced from single frequency flat-*B* (spatial domain) source experiments [3-7] and by injecting multiple discrete frequency microwave radiation to form multiple ECR zones in conventional-*B* geometry ECRISs (frequency domain) [8-10]. However, the practical application of the latter technique is very costly, requiring multiple independent single-frequency *rf* power supplies and complicated *rf* injection systems. Broadband sources of *rf* power offer a low-cost and more effective alternative for increasing the physical sizes of the ECR zone within these sources. Such broadband sources of *rf* power were not available from non-military resources when this idea was first proposed [2] but are now commercially available [11]. Although, developed primarily for powering conventional-*B* geometry ECRIS, the device offers the prospect of ameliorating diamagnetic frequency detune effects, believed to be problematical in plateau ECR ion sources. The present article describes initial use of the AWGNG for powering the ORNL flat-*B* ECRIS.

THE BROAD BAND FREQUENCY GENERATOR

Noise with power evenly distributed over all *rf* and microwave frequencies is called "white-noise". The AWGNG, used for the experiments reported in this document, has an output central frequency range of 5.85 to 6.65 GHz with bandwidth at each frequency of 200 MHz [12]. The noise-generating instrument is programmable, with selectable attenuation levels, time delays and incremental attenuation step values. Figure 1 shows a *rf* spectrum from the AWGNG, operating at a central frequency of 6.2 GHz with bandwidth of ~200 MHz, prior to amplification with the TWTA.

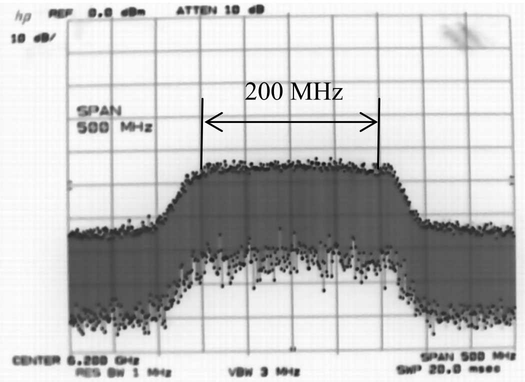

Figure 1: Output from the noise generator at a central frequency of 6.2 GHz.

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Retrofitting existing ECRISs can be easily accomplished by inserting the noise generator between the single-frequency signal generator (local oscillator (LO)) and the TWTA. The signal from LO is fed into the noise generator that generates noise equally distributed (± 100 MHz) about the central frequency of the local oscillator (LO) minus 1.8 GHz. The central frequency of the LO frequency can be changed anywhere within the band-pass of the TWTA (~800 MHz).

EXPERIMENTAL SETUP

The performances of the 6 GHz, all-permanent-magnet ORNL flat-*B* ECR ion source [3,13] were evaluated *with* and *without* the AWGNG. Signals from the ~1 MHz bandwidth LO were injected directly into the TWTA for amplification to the desired power for the narrow bandwidth (single-frequency) experiments and from the 200 MHz broadband white-noise generator for the broadband experiments. The LO signal generator was also used to provide input signals to the "white-noise" generator. Microwave power was injected into the plasma chamber through an on-axis rectangular-to-circular tapered traveling wave injection system. Forward and reflected powers were monitored at a location close to the microwave injection window. All comparative measurements were made using Ar gas. The intensities of Ar^{8+} were optimized in terms of pressure, microwave power and microwave frequency while keeping the Ar flow rate constant during each series of measurements. Ion beam intensities were monitored in electron suppressed Faraday cups located before and after magnetic mass analyses. *X*-ray emission was observed along the axis of the plasma chamber with an *X*-ray detector [14].

RESULTS AND DISCUSSION

Figure 2 shows total ion beam intensities (measured prior to magnetic analysis) and Ar^{8+} intensities (measured after magnetic analysis) as a function of microwave frequency. The best performance with single frequency microwave was obtained at ~6.155 GHz which corresponds to the resonant frequency of the flat part of the magnetic field. Ion beam intensities exhibit strong fluctuations in intensity with slight changes in frequency and microwave power during single frequency operation. In order to maximize ion beam intensity, it was necessary to decrease the injected power from 50 to 30 W with increases in frequency. In the region of 6.225 GHz and below, it was necessary to increase the injected power up to ~100 W to realize maximum beam intensities. When single frequency microwave radiation was injected, the intensity was found to be very sensitive to changes in frequency as noted in Fig. 2(a) and was observed to drop whenever the injection frequency was adjusted away from resonance (plateau region of the field). In contrast with single frequency operation, although mode changes were also observed, intensity fluctuations with changes in frequency were much less sever when broadband microwave radiation was utilized, as observed in Fig. 2(b). The injected microwave power used in these measurements was in the range of 30 to 50 W, except in the region below 6.2 GHz where microwave power up to 150W was necessary to maximize ion beam intensity. Maximum Ar^{8+} intensities was observed whenever the central frequency was ~ 6.15 GHz, (about the same as observed in the single frequency experiments) and whenever the central frequency was adjusted to ~ 6.45 GHz (above the ECR resonant condition for the plateau region of the magnetic field). However, when the central frequency is tuned to the resonant plateau region of the magnetic field using broadband microwave radiation, ion beam intensities are less than those with single frequency microwave power, presumably, because of the reduced power density within the plateau field region (ECR zone). (These intensity deficits could not be compensated for by increasing the broadband microwave power.)

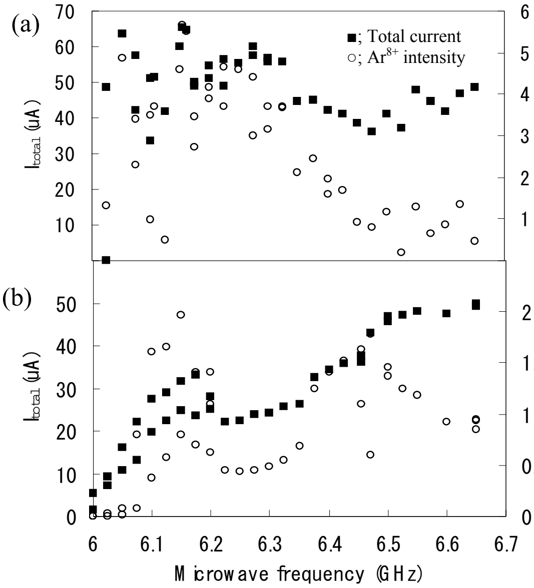

Figure 2: Total beam intensity and Ar^{8+}beam intensity as functions of microwave frequency with (a) single and (b) broadband microwave power.

Differences with single and broadband frequency microwave power are also clearly seen in the reflected power ratio shown in Fig. 3. With single frequency microwave power, the ratio of reflected power to forward power strongly fluctuates. These data show a smoother transition when broadband radiation is used. As noted, reflected power decreases with frequency. These observations might suggest that plasma stability is better whenever broadband microwave radiation is used to power the source, in keeping with the ameliorating effect of broadband radiation on diamagnetic detune problems that must occur in plateau ECR ion sources with fixed resonant magnetic field volumes.

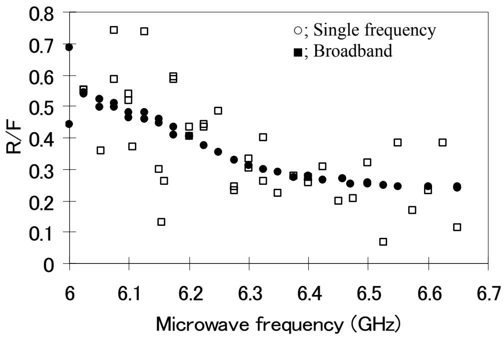

Figure 3: Ratio of reflected power to forward power as a function of microwave frequency.

The injection of broadband microwave radiation is expected to enhance the performance of ECR ion sources with conventional minimum-*B* magnetic field configurations. In order to address this issue, the performance of the source was compared *with* and *without* injection of broadband microwave radiation with the magnetic field adjusted to the frequency region of ~6.4 GHz and above, far away from the resonant plateau field region.

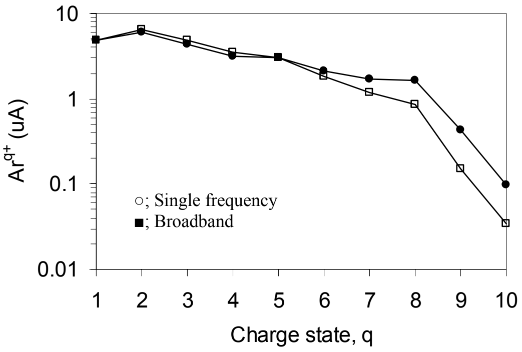

Figure 4: Charge-state distribution of Ar ions.

Figure 4 compares charge-state distributions of Ar at 6.457 GHz obtained with single and broadband frequency microwave radiation, respectively. The frequency was tuned to obtain intensity maxima with single frequency radiation; the intensity was not observed to be very sensitive to changes in central frequency when broadband microwave power was used, as expected. However, the maximum intensity was also observed to occur at the same frequency used to maximize single frequency operation. The forward and reflected powers were, respectively, 29.2 W and 7.38 W for single frequency operation and 26.2 W and 7.0 W respectively, for broadband frequency operation. The total ion beam intensities were 33.7 μA and 34.9 μA with single frequency and broadband microwave power, respectively. As noted, the intensities for charge state $q > 6$ are higher for the broadband microwave frequency mode of operation. When the frequency is adjusted away from the plateau region of the magnetic field distribution, the ECR zone is larger when the source is operated with broadband microwave radiation and consequently, a larger population of electrons should be accelerated to higher energies. However, we did not observe significant differences in the *X*-ray spectra for the two cases.

CONCLUSIONS

A new concept broadband microwave generator (AWGNG) has been initially and successfully used to power the all-permanent-magnet, 6 GHz, ORNL plateau ECR ion source. Broadband power was found to moderate the extreme fluctuations in ion beam intensity observed with single frequency operation. The fact that the ion beam intensity and charge state distribution were improved when the central frequency was tuned to the off plateau region of the magnetic field suggests that the device will be an effective means for enhancing the performances of conventional minimum-*B* ion sources. Experiments are planned to evaluate the conventional form of the 6 GHz ORNL source *with* and *without* broadband microwave radiation in the near future.

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